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<u>Final Scientific Report for Grant AFOSR 76-3037</u>

Results of research supported by Grant AFOSR 76-3037 have been presented by the principal investigator and the research assistants in the following papers:

(1) Harville, D.A., "Maximum Likelihood Approaches to Variance Component Estimation and to Related Problems", Journal of the American Statistical Association, Volume 72, Number 358, June 1977, Pages 320-340 (Invited paper, with discussion by J.N.K. Rao and a rejoinder by the author).

(2) Harville, D.A., "Alternative Formulations and Procedures for the Two-Way Mixed Model", Biometrics, Volume 34, Number 3, September 1978, Pages 441-453.

(3) Harville, D.A., "Some Useful Representations for Constrained Mixed-Model Estimation", Journal of the American Statistical Association, Volume 74, Number 365, March 1979, Pages 200-206.

(4) Harville, D.A., "Recursive Estimation Using Mixed Linear Models with Autoregressive Random Effects", In Variance Components and Animal Breeding: Proceedings of a Conference in Honor of C.R. Henderson, L.D. Van Vleck and S.R. Searle, editors, Ithaca, New York: Cornell University, 1979, Pages 157-179 (Presented at the conference on July 17, 1979 as an invited paper).

(5) Harville, D.A., "Unbiased and Minimum-Variance Unbiased Estimation of Estimable Functions for Fixed Linear Models with Arbitrary Covariance Structure", The Annals of Statistics, Volume 9, Number 3, May 1981, Pages 633-637.

(6) Kackar, R.N., and Harville, D.A., "Unbiasedness of Two-Stage Estimation and Prediction Procedures for Mixed Linear Models". Communications in Statistics, Part A: Theory and Methods, Volume A10, Number 13, 1981, Pages 1249-1261.

(7) Kackar, R.N., and Harville, D.A., "Variance Approximations for Two-Stage Estimation and Prediction Procedures for Mixed Linear Models", 1980 Proceedings of the Statistical Computing Section of the American Statistical Association, Pages 52-58 (Presented by Kackar at the 1980 Annual Meeting of the American Statistical Association, Houston, Texas, as an invited paper).

(8) Sallas, W.M., and Harville, D.A., "Best Linear Recursive Estimation for Mixed Linear Models", To appear in the September 1981 issue of the Journal of the American Statistical Association (Presented by Sallas at the 1980 Annual Meeting of the American Statistical Association, Houston, Texas).

(9) Harville, D.A., "Simple Proofs for Two Theorems on the Distribution of Quadratic Forms", To be submitted to Communications in Statistics, Part A: Theory and Methods.

(10) Mee, R.W., and Harville, D.A., "Analysis of Ordered Categorial Responses, Assuming an Underlying Continuous Variable", To be submitted to the Journal of the American Statistical Association.

Results of research supported in part by the Grant were also presented in the following documents:

(11) Sallas, W.M., "Some Relationships Between Linear Models and Kalman Filtering", Creative Component for M.S. degree, Iowa State University, May 1977.

(12) Sallas, W.M., "Recursive Mixed Model Estimation", Ph.D. Dissertation, Iowa State University, August 1979.

(13) Kackar, R.N., "Variance Approximations for Estimators of Fixed and Random Effects in Mixed Linear Models", Ph.D. Dissertation, Iowa State University, August 1979.

(14) Harville, D.A., "A Generalized Version of Albert's Theorem and Its Application to the Mixed Model", Unpublished manuscript, August 1980.

(15) Christenson, P.D., "Notes on the Extended Version of the Generalized Gauss-Markov Theorem", Creative Component for M.S. degree, Iowa State University, September 1980.

(16) Mee, R.W., "Analysis of Ordered Categorical Responses, Assuming an Underlying Continuous Variable", Ph.D. Dissertation, Iowa State University, August 1981.

Research that closely supported the Grant research, but which was not supported financially by the Grant, was presented in the following papers:

(17) Harville, D.A., "The Use of Linear-Model Methodology to Rate High School or College Football Teams", Journal of the American Statistical Association, Volume 72, Number 358, June 1977, Pages 278-289.

(18) Harville, D.A., "Football Ratings and Predictions Via Linear Models", 1978 Proceedings of the Social Statistics Section of the American Statistical Association, Pages 74-82 (Presented at the 1978 Annual Meeting of the American Statistical Association, San Diego, California, as an invited paper).

(19) Harville, D.A., "Predictions for National Football League Games Via Linear-Model Methodology", Journal of the American Statistical Association, Volume 75, Number 371, September 1980, Pages 516-524.

Salary savings from the Grant were used to employ Lynn R. LaMotte for June-July 1978. LaMotte used this period to pursue his work on linear models. Financial support was provided by the Grant for trips to Iowa State by Carl N. Morris (February 1-2, 1977), Friedrich Pukelsheim (November 28-29, 1977), R. Dennis Cook (May 1-2, 1979), Kenneth G. Brown (April 22-23, 1980), and Justus F. Seely (April 29-30, 1981) for purposes of consulting with the principal investigator.

The Grant-related research centered on the following five topics:

(a) The estimation of variance components and related problems. The paper (1) presented a unified review of the maximum likelihood and restricted maximum likelihood techniques for estimating variance components. The emphasis was on computational aspects and relationships to other procedures. Various approximate techniques that were suggested in the paper (1) were applied to college and professional football data in order to get some feeling for the kinds of difficulties that might be encountered in practical applications. The results were reported in papers (17) - (19). The paper (2) included comparisons of several procedures for estimating variance components.

(b) Inference for linear combinations of the fixed and random effects in mixed linear models. In the paper (3), normal-like equations derived by C.R. Henderson for mixed-model computations were extended to the case where there are constraints on the fixed effects. Extensions to the case where the covariance matrix of the model's residual effects is singular were considered in (15). Various inference procedures for fixed and random effects were compared in the paper (2) in the context of the two-way mixed model. Two-stage procedures for estimating fixed and random effects (which consist of first estimating the variance components and then using the estimators of the effects that would be best linear unbiased if the variance component estimates were treated as true values) were considered in (6), (7) and (13). It was shown, under fairly unrestrictive conditions, that the two-stage estimators of the effects are unbiased. Also, variance approximations for the two-stage estimators were devised. The estimation of fixed effects when the covariance matrix of the data vector is known, but is singular, was considered in the paper (5). Properties of estimators of the "pseudo-linear" type were derived.

(c) Recursive estimation. Recursive estimation techniques for fixed and completely random models were extended to mixed models. The results were presented in (4), (8), and (12) and were tried out on the football data, as reported in (18) and (19).

(d) Distribution of quadratic forms in normal random variables. Simplified proofs were devised for generalized versions of two fundamental theorems on the distribution of quadratic forms. They were presented and discussed in the paper (9). The paper (14) presented a generalized version of a theorem due to A. Albert on the distribution of quadratic forms and described its relationship to Cochran's theorem and its application to the mixed model.

(e) "Linear" inference from ordered categorical data. Methodology was developed for the analysis of data having an ordered categorical response. The underlying model was taken to be the threshold model, which is based on the assumption of the existence of an underlying continuous random response variable that follows a fixed, mixed, or random linear model. The approach incorporates concepts from maximum likelihood and best linear unbiased estimation. Results for the fixed-model case are given in (10) and (16). Extensions to mixed and random models are described in (16).